China-Japan International Academic Symposium
Environmental Problem in Chinese Iron-Steelmaking Industries
and Effective Technology Transfer
Sendai, Japan, 6, March 2000

NUMERICAL SIMULATION ON MULTI-SMELTER FOR MELTING WASTE MATERIALS

Jun-ichiro Yagi[*1], Reijiro Takahashi[*1], Xinghe Zhang[*1] and Shoichi Kume[*2]

*1 Institute for advanced Materials Processing, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai, 980-8577, JAPAN
Tel: +81-22-217-5172, Fax: +81-22-217-5211
E-mail: yagi@iamp.tohoku.ac.jp

*2 Institute for Reduction and Smelting Technology Inc.
1-13-34, Nijinooka, Izumi-ku, Sendai, 981-8007, JAPAN
Fax/Tel: +81-22-372-3932

ABSTRACT

A coke packed bed process is effective to melt industrial waste materials like used TV sets, air conditioners, refrigerators and so on without secondary emission of dangerous materials like dioxin. Melting the waste materials can highly reduce the volume of the waste materials compared to the combustion. This makes these dispose easier. Such a process called “Multi-Smelter” which can treat the waste materials of 1 ton/day has been constructed at Osaka Prefecture University and has been operated successfully. Numerical simulation has been attempted for estimating the internal conditions of the “Multi-Smelter” process. At present, internal temperature distributions have been obtained for the different operation conditions. This gives effective information of the process for improving the operations leading to less energy consumption and more waste materials treatment.

1. INTRODUCTION

Much attention is focussed on the waste materials processing. Recently, 50 million tons of municipal waste materials and 400 million tons of industrial waste materials have been generated every year in Japan. Among them, metallic wastes from the industries are estimated as 30 million tons per year [1]. It is strongly required that the waste materials must be reduced as low as possible and remaining wastes should be effectively used as resources for the other purposes for protecting environments and also for reserving finite deposits of fossil energy and natural resources.

Many processes for incinerating or melting the waste materials has been attempted to be developed in Japan. Amongst these processes [2], a packed bed melting furnace has recently received high evaluations because the process can eliminate toxicity and reduce significantly the volume. Specifically, a multi-smelter [1] is expected to be a promising process for melting metallic wastes, which are changed to reusable materials without generating dioxin.

Figure 1 illustrates a schematic representation of a multi-smelter, which consists of coke packed bed in the lower part, and free board where fine materials are fluidized during operation. This furnace is furnished with some tuyeres at the different levels: two levels in the packed bed and one level in the free board. Oil burners are equipped at the slag outlet and at the free board respectively for auxiliary heating when low thermal level is observed at the lower part of the packed bed.

Waste materials and coke are charged at the top of the packed bed. Light materials like plastics are mainly burned or gasified in a fluidized bed condition in the free board and heavy materials like metals dropped to the top of the packed bed and are heated with gas flow then reduction reaction and/or melting proceed. Molten slag and metals are discharged from the tapping hole.

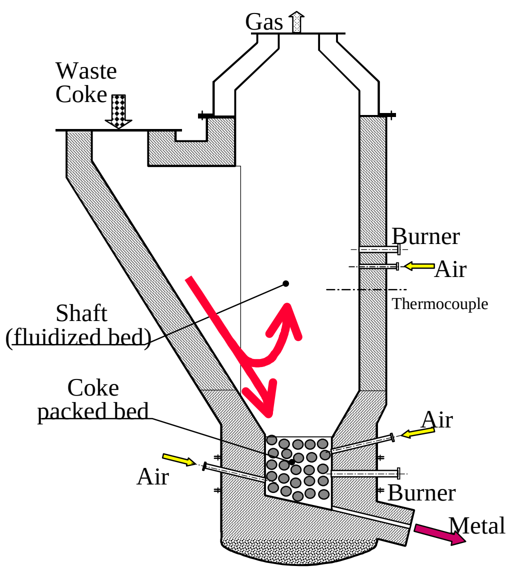

Fig.1 Conceptual scheme of a multi-smelter for waste melting.

In this multi-smelter, the packed bed part seems to play an important role for melting metallic wastes effectively and for achieving a stable operation. On the basis of this foresight, a mathematical model has been proposed, which considered transport phenomena of heat, mass and momentum together with melting and chemical reactions for melting waste materials. Numerical simulation was conducted to investigate in-furnace phenomena and effects of operating conditions on the process stability. As a result, the multi-smelter was found to be a useful process for melting some kind of waste materials like used refrigerators, air-conditioners, the major part of which were originally made from iron and plastics.

2. MATHEMATICAL MODEL

Figure 2 illustrates a packed bed part of the multi-smelter for the numerical analysis, which consists of a cylindrical coke packed bed of 0.5m in diameter and 0.58m in height. In the packed bed, three phase of gas, liquid and packed particles coexist. Among these three phases, momentum, heat and mass exchanges take place together with melting of the metallics, chemical reactions and combustion of coke in the vicinity of tuyeres.

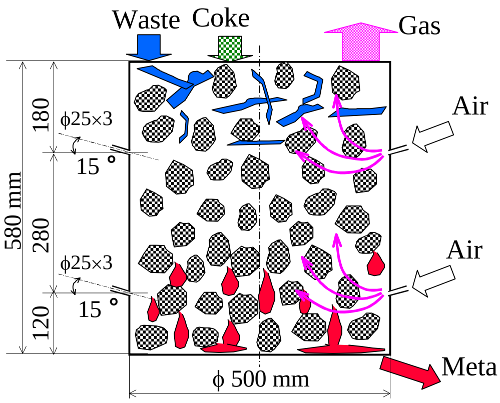

Fig. 2 Mathematical modeling of packed bed in a multi-smelter.

2.1 Fundamental Equation

A general expression for momentum, heat and mass transfer with sink and source is described as Equation (1) for three phases in the two-dimensional cylindrical coordinate system.

$$\frac{\partial(\varepsilon_i\rho_i u_i\phi_i)}{\partial x}+\frac{1}{r}\frac{\partial(r\varepsilon_i\rho_i v_i\phi_i)}{\partial r}=\frac{\partial}{\partial x}(\Gamma_{\phi_i}\frac{\partial\phi_i}{\partial x})+\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_{\phi_i}\frac{\partial\phi_i}{\partial r})+S_{\phi_i} \tag{1}$$

Where, subscript i in Eq.(1) expresses gas, liquid and solid (g, s, l) three phases. ϕ designates process variables of vertical velocity (u), horizontal velocity (v), mass (1), enthalpy (h) and mass fraction (m). Γ is transport coefficient and S is source term.

However, for packed particles, kinematic model [3)] is applied because this model is simple and has enough simulation precision for a straight cylindrical reactor.

2.2 Evaluation of Effective Contact Area between Different Phases

In the multi-smelter, three phases of gas, liquid and packed particles occupy packed bed region and the liquid hold up is assumed to be dynamic hold up only. Equation (2) can be written for the volume occupation fraction in a packed bed.

$$\varepsilon_g+\varepsilon_s+\varepsilon_l = 1 \quad (2)$$

Effective contact area between gas and liquid, a_{gl} is estimated by Eq.(3)[4] and that between liquid and solid, a_{ls} is calculated from Eq.(4)[5]. Then, effective contact area between gas and solid can be calculated by subtracting a_{ls} from particles surface area as described in Eq.(5).

$$a_{gl}=0.34 Fr_{ls}^{-1/2} We_{ls}^{2/3}/d_s \quad (3)$$

$$a_{ls}=\frac{6\varepsilon_s}{d_s}\{0.4(Re_{ls}/\varepsilon_s)^{0.218} We_{ls}^{00428} Fr_{ls}^{-0.0238} Nc^{-0.0235}\} \quad (4)$$

$$a_{gs}=\frac{6\varepsilon_s}{\psi d_s}-a_{ls} \quad (5)$$

2.3 Interaction Parameters

The interaction parameter between gas and solid phases is given by modified Ergun's relation [6] for considering liquid coexistence, which is expressed by Eq. (6).

$$\vec{F}_{gs}=\left\{\frac{150\mu_g a_s a_{gs}}{36(1-\varepsilon_s)}+\frac{1.75\rho_g a_{gs}}{6}|\vec{v}_g-\vec{v}_s|\right\}(\vec{v}_g-\vec{v}_s) \quad (6)$$

The interaction parameter between gas and liquid is calculated by Eq. (7), which is derived by modifying Fanning equation [7] for effective contact area between gas and liquid.

$$\vec{F}_{gl}=\frac{a_{gl}}{a_{gl}+a_{sl}}\ \frac{3C_D\rho_g\varepsilon_l}{4d_l}|\vec{v}_g-\vec{v}_l|(\vec{v}_g-\vec{v}_l) \quad (7)$$

The size of a liquid droplet is estimated from Eq. (8) [8]. This equation is derived as the maximum size of the droplet passing through the densest packing of packed bed.

$$d_l=\frac{2\times\sqrt{3}-3}{3}d_s \quad (8)$$

The liquid-solid interaction parameter can be obtained from the Kozeny-Carman [9] equation modified for the effective contact area as described by Eq. (9).

$$\vec{F}_{ls}=\frac{180\mu_l a_s a_{sl}}{36(1-\varepsilon_s)}(\vec{v}_l-\vec{v}_s) \quad (9)$$

2.4 Heat Transfer Coefficient

Convective heat transfer coefficients between gas and solid and between gas and liquid are obtained from Ranz and Marshall's equation modified by Akiyama et al [10] for packed bed processes as expressed by Eqs. (10) and (11).

$$h_{gs}=(2.0+0.39Re_{gs}^{1/2}Pr_g^{1/3})\lambda_g/d_s \quad (10)$$

$$h_{gl}=(2.0+0.39Re_{gl}^{1/2}Pr_g^{1/3})\lambda_g/d_l \quad (11)$$

The solid-liquid convective heat transfer coefficient can be obtained from equation (12) given by Pohlhausen [11] for forced convection.

$$h_{ls}=(0.664Re_{ls}^{1/2}Pr_l^{1/3})\ \lambda_l\ /d_s \qquad (12)$$

2.5 Chemical Reactions

Chemical reactions considered in the mathematical model are listed in **Table 1** together with melting of iron, which is a phase change. Rates of chemical reactions are derived as follows.

Table 1 Reactions in a multi-smelter.

	Reaction	No.	Reaction rate
Combustion & gasification of coke	$C + 1/2\ O_2 = CO$ $C + O_2 = CO_2$ $C + CO_2 = 2CO$ $C + H_2O = CO + H_2$	1 2 3 4	Muchi et al. [12] (1966)
Gaseous	$CO + 1/2\ O_2 = CO_2$ $CO + H_2O = CO_2 + H_2$ $H_2 + 1/2\ O_2 = H_2O$	5 6 7	Howard et al. [13] (1973)
Carburization	$2CO = C_{(in\ Fe)} + CO_2$	8	Zhang et al.[14] (1997)
Melting	Fe(s) = Fe(l)	9	

An expression of overall reaction rate considering chemical reaction and diffusion through gaseous film, which was derived by Muchi et al 12), is used for combustion and gasification of coke. Howard's rate equation[13] is applied to combustion of CO and equilibrium is assumed for combustion of H_2 and water gas shift reaction.

Carburization rate of iron was obtained experimentally in previous study[14] where carburization reaction at iron surface from CO gas and diffusion of carbon in solid iron were considered. The carburization rate is applied to the mathematical model.

Melting rate of iron is calculated from Eq. (13), which is derived by assuming heat transfer rate as the rate-limiting step.

$$R_m=a_{gs}h_{gs}(T_g- T_m)/\Delta H_m \qquad (13)$$

3. SIMULATION

3.1 Simulation Condition

3.1.1 Properties of Charged Materials

Table 2 lists compositions of wasted electrical appliances used for melting experiments. Wasted refrigerators, air conditioners and washers contain oven 50% iron. However, Wasted TV sets contains less metals and the main component is glass. In the numerical simulation composition of the wasted refrigerators is used. Plastics contained do not enter the packed bed due to low density therefore only iron is considered for melting analysis. Coke used is assumed to consist of 90% fixed carbon and 10% ash. **Table 3** lists physical properties of burden materials.

Table 2 Composition of wasted electrical appliances (mass%).

	Fe	Cu	Al	Plastics	Glass	Wood	Others
Refrigerator	50	4	3	40	0	0	3
Air Conditioner	55	17	7	11	0	0	10
Washer	53	4	3	36	0	0	4
TV set	10	3	2	23	57	5	0

Table 3 Physical properties of charged materials.

Charged Material	Diameter (mm)	Porosity (-)	Shape Fraction (-)	True Density (kg/m^3)
Coke	30	0.51	0.74	1000
Refrigerator (Fe)	20	0.60	0.50	7800

3.1.2 Operating Conditions

Table 4 lists main operating conditions. Blast temperature is selected as 298 K for the case where coke is only charged, while selected as 773 K for melting wasted refrigerators. Theoretical air volume for complete combustion of the supplied oil is introduced to a burner. Amount of coke charged is obtained as simulation results.

Table 4 Operation conditions without and with refrigerators charging.

Material	Coke bed only		Refrigerators melting	
	Feed rate ($\times 10^{-3}$ kg/s)	Temperature (K)	Feed rate ($\times 10^{-3}$ kg/s)	Temperature (K)
Air (Blast)	39.1	298	39.1	773
Coke	7.84	298	7.84	298
Air (Burner)	9.5	298	9.5	298
Oil (Burner)	0.67	298	0.67	298
Refrigerator (Fe)	-	-	15.7	298

3.2 Simulation Results and Discussion

3.2.1 Temperature Distribution for Coke Bed

Figure 3 represents temperature distributions of gas and coke particles in the multi-smelter for charging only coke. Air is supplied at 298 K through two slits. The air combusts with coke increasing temperature rapidly up to around 2000 K in the vicinity of the slits. High temperature region around the lower slit extends wider than that of the upper slit due to the oil burner equipped at the lower slit. In the peripheral region, lower temperature about 1400 K appears between upper and lower slit and under the lower slit. This is due to high heat loss through the wall.

On the other hand, coke charged at the top of the packed bed is heated rapidly by the heat exchange with ascending high temperature gas. The coke packed bed shows very high temperature around the upper and lower slits similar to gas temperature. The highest temperature of the coke around the lower slit is higher than that around the upper slit by about 100 K. This difference is mainly caused by the oil burner. To compare coke temperature with gas temperature, the former shows more gentle distribution.

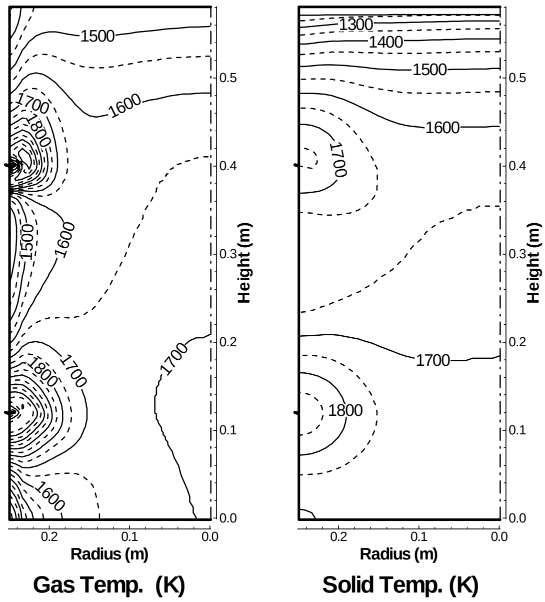

Fig.3 Computed isotherms in multi-smelter for charging coke only.

Figure 4 shows axial distributions of average temperatures of gas and coke. The average temperature distribution of gas has two peaks at the two slit levels, which show 1800, and 1950 K, respectively. The average temperature of gas at lower slit level is higher than that at upper slit level by 150 K. As being away from the both slit levels, the temperature decreases sharply. Gas temperature is lower than the coke temperature in the areas between upper and lower slit and under lower slit. Outlet gas temperature at the top of the packed bed is about 1450 K. For the temperature of coke, two temperature peaks appear at the both slit levels similar to gas temperature. However, coke temperature distribution shows more gentle change than that of gas.

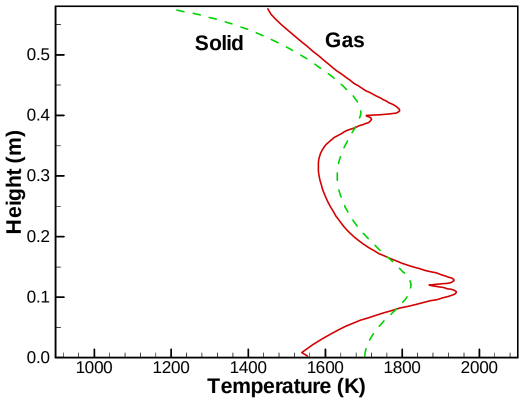

Fig.4 Longitudinal temperature distributions of gas and solids in coke bed.

3.2.2 Temperature Distribution for Refrigerators Melting

Figure 5 shows the temperature distribution of the gas, solid and liquid in the multi-smelter for melting refrigerator shredders.

The air preheated to 773 K was blown from the tuyere. It was rapidly heated to over 2000 K around the upper and the lower tuyeres by the combustion with the coke. As being similar to the previous coke packed bed, high-temperature region near the lower tuyere is wider than that near the upper tuyere by the combined effects of lump coke supply at higher temperature to the lower tuyere region and combustion heat from kerosene burner installed at the lower tuyere level. At the furnace sidewall between upper and lower tuyeres and under the lower tuyere, low-temperature region of about 1400K was formed as similar to the previous coke packed bed by marked heat loss through furnace wall.

The solid (coke and refrigerator shredder) was rapidly heated by the heat exchange with ascending high-temperature gas, when charged from the furnace top at room temperature.

The iron melting started just above the upper tuyere level. The coke temperature further rose below the melting zone shown in 2 dotted lines in Fig.5. However, the high-temperature region is formed near the upper and lower tuyere regions as being similar to the gas temperature distribution, and coke temperature near the lower tuyere is higher than that near the upper tuyere. The melting zone was thin. The width was about 0.1m from the start to the end of melting.

The molten pig iron was heated by both coke and gas below the melting zone, and it did not show large temperature gradient in radial direction. At the sidewall, the molten pig iron temperature did not decrease in spite of low gas temperature.

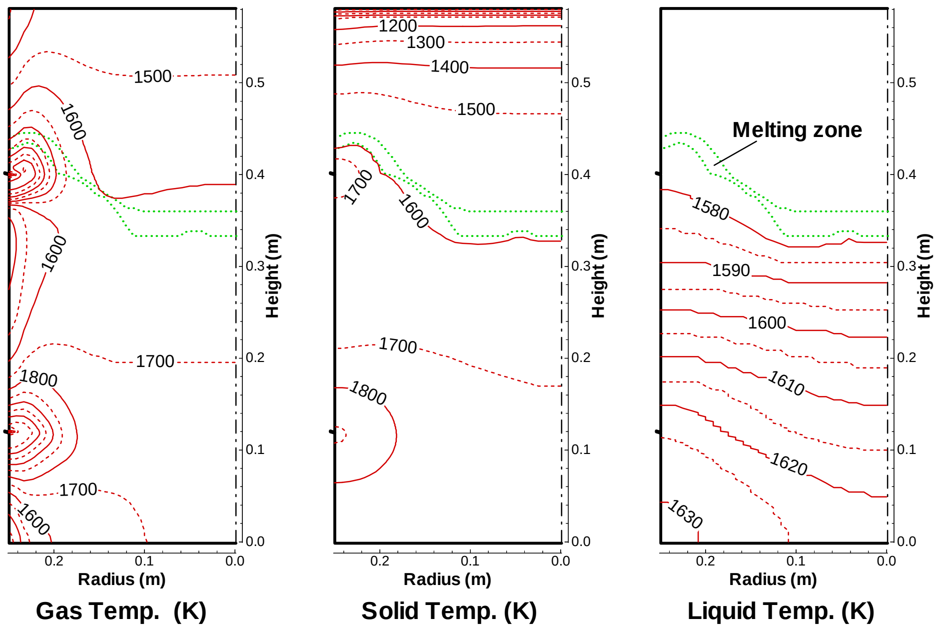

Fig.5 Computed isotherms in multi-smelter for refrigerators melting.

4. CONCLUSION

A two dimensional mathematical model has been developed for analyzing a multi-smelter which was constructed for treating industrial waste materials. Numerical analysis has been conducted for some operations of the multi-smelter, for examples, only coke charging and refrigerator shredders charging. As the results, process characteristics such as distributions of concentration, temperature and velocity have been obtained, which are useful to evaluate the performance of the multi-smelter and to improve the operations.

NOMENCLATURE

A	Heat transfer area in free board [m^2]
a	Area [m^2/m^3(bed)]
C_D	Drag coefficient [-]
C_p	Specific heat [J/kg-K]
d	Mean particle diameter [m]
d_c	Mean particle diameter of coke [m]
$\vec{F}$	Volumetric momentum flux [N/m^3]
Fr	Froude number ($= a_j G_i^2 / \rho_i^2 g$) [-]
$F_{r,ij}$	Radial interaction force between i and j phases [N/m^3]
$F_{x,ij}$	Vertical interaction force between i and j phases [N/m^3]
G	Mass flow rate [kg/m^2s]
g	Gravitational force [m/s^2]
ΔH^c	Enthalpy transfer [W/m^3(bed)]
h	Enthalpy [J/kg]
h_{ij}	Heat transfer coefficient between *i* and *j* phases [W/m^2-K]
m	Fractional mass [-]
N_c	Dimensionless surface tension N_c=(1+cosθ) [-]
Nu_m	Nusselt number ($=h_g d_{shaft}/\lambda_g$) [-]
P	Pressure [Pa]
Pr	Prandtl number ($=\mu Cp_t/\lambda$) [-]
Q	Heat loss at lower free board part [J/s·K]
Q_{loss}	Rate of heat loss at packed bed [W/m^2K]
R	Gas constant [J/mol-K]
r	Radial distance [m]
Re	Reynolds number ($= G_i d_j / \mu_i$) [-]
R_k	Reaction rate of k-th reaction [kg/s-m^3(bed)]
R_m	Melting rate [kg/s-m^3(bed)]
S	Source term [kg/s-m^3(bed), N/s-m^3(bed), J/ s-m^3(bed)]
S_{sg}	Mass transfer from solid to gas [kg/s-m^3(bed)]
T	Temperature [K]
T_m	Melting point [K]
u	Vertical velocity [m/s]
v	Radial velocity [m/s]
$\vec{v}$	Velocity vector [m/s]
We	Weber number ($= G_i^2 / a_j \rho_i \sigma_i$) [-]

x Vertical distance [m]

Greek

Γ Diffusive transport coefficient [kg/m-s]

ε Volumetric fraction [m^3/m^3(bed)]

η Distribution ratio of reaction heat [-]

θ Contacting angle [degree]

λ Thermal conductivity [W/m-K]

μ Viscosity [Pa s]

ν Stoichiometric coefficient [-]

ρ Density [kg/m^3]

σ Surface tension [N/m]

ϕ Dependent variable

ψ Shape fraction of particle [-]

Subscription

a Average

g Gas

i,j Phase

k Reaction number

l Liquid

ng Gas species (O_2, CO_2, H_2O, CO, H_2, N_2)

ns Solid species (Coke, Fe(s))

REFERENCES

1) Ohnishi T., Kume S.: Journal of high temperature society, **25** (1999), 53.
2) Yoshida T.: Development trend of the Systems for Thermal Decomposition and Gasification-Ash Melting, NTS Publisher, (1998).
3) Wang J., Takahashi R. and Yagi J.: Kagaku Kogaku Ronbunshu, **17** (1991), 179.
4) Mada J., Shinohara H. and Tsubakihara M.: Kagaku Kougaku, **27** (1963), 978 - 982.
5) Niu M., Akiyama T., Takahashi R. and Yagi J.: Tetsu-to-Hagane, **82** (1996), 647 - 652.
6) Ergun S:, Chem. Eng. Progr., **48** (1952), 89 - 94.
7) Hatta S., Maeda S.: Introduction to Chemical Engineering (Japanese), Kyoritsu-Shuppan, (1978), 270.
8) Sugiyama T., Nakagawa T., Shibaike H. and Oda Y.: Tetsu-to-Hagane, **73** (1987), 2044.
9) Chemical Engineers' Handbook, 5th edition, Society of Chemical Engineers (Japan), Muruzen, (1988), 247.
10) Akiyama T., Takahashi R. and Yagi J.: Tetsu-to-Hagane, **76** (1990), 848 - 855.
11) Hiraoka M. and Tanaka M.: Transport Phenomena, Asakura-shoten, (1971), 102.
12) Kuwabara M., Hsieh Y. and Muchi I.: Tetsu-to-Hagane, **66** (1980), 1918.
13) Howard J. B., Williams G. C. & Fine D. H.: 14th Int. Symposium on Combustion, Pittsburgh (1973), 975.
14) Zhang X., Takahashi R. and Yagi J: Tetsu-to-Hagane, **83** (1997), 299 - 304.